Analysis of Satellite Observations for the Coastal Mixing and Optics Program

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LONG-TERM GOALS

The long-term scientific goal of this effort is to understand the advantages and limitations involved in extracting quantitative information of oceanographic importance from Synthetic Aperture Radar (SAR) imagery of the ocean surface.

OBJECTIVES

The principal scientific objectives of our research are to improve understanding of the physics that governs the imaging of oceanographic features such as internal waves, surface waves, and water-mass boundaries by SAR, and to use this understanding to provide a 2-dimansional overview of the ocean surface from which important oceanographic parameters can be reliably estimated. Our effort is unique in that it is supported by a large variety of *in situ* measurements, including density and current profiles, two-dimensional surface-wave spectra, and standard meteorological measurements, collected as part of the Coastal Mixing and Optics (CMO) experiment.

APPROACH

We have analyzed and archived all available RadarSat and ERS-2 SAR imagery over the CMO experimental area during the active phases of the experiment in August and September 1996 and the mooring-recovery cruises in the summer of 1997. The RadarSat SAR imagery was obtained as part of an Application Development and Research Opportunity (ADRO) grant from the Canadian Space Agency [Thompson, *et al*., 1998]. The ERS-2 imagery was acquired from the European Space Agency (ESA) through a collaboration with the Institute of Oceanography at the University of Hamburg. Each of these images (19 RadarSat and 11 ERS-2) is displayed on our CMO web page located at URL: http://fermi.jhuapl.edu/cmo/cmo_index.html. We have correlated parameters extracted from this imagery with the extensive *in situ* measurements during CMO as well as those collected routinely from buoys, tide gauges, and meteorological stations in the area. These correlations and comparisons, coupled with results from our imaging models, have provided a unique opportunity to validate and improve our understanding of the imaging physics and ultimately the utility of spaceborne SAR as a practical tool for oceanographic research.

WORK COMPLETED

- The entire SAR data set was analyzed, geo-located, and displayed on our web page along with commentary on particular passes, ancillary AVHRR imagery, and meteorological data from the CMO moorings and nearby NDBC buoy data,. This web page is open to the CMO investigators as well as all other interested researchers in the scientific community.

- A web based CMO data time-line was created linking all research components and online data files and reports.

- The SAR data was used to validate a method for estimating the depth and density of the surface layer proposed by Porter and Thompson, [1999].

- Comparisons were made between surface-wave spectra measured by the 2-D wave buoy deployed at the CMO experimental site and those derived from the SAR imagery. These comparisons were particularly interesting during the time period when Hurricane *Edouard* passed near the CMO site in early September 1996.

- The SAR intensity modulations caused by tidal current flow over the Nantucket Shoals have been correlated with tidal current predictions. Characterization of variability in the image time series over this area as a function of the phase of the tidally-induced surface current and the local wind field is currently near completion as part of a masters-degree thesis project at JHU.

RESULTS

Figure 1 is a blowup of the CMO experimental area extracted from a RadarSat image (Orbit 8209) collected on 31 May 1997 at 22:36 UT and sampled with 50-m pixel spacing. The four small white squares in the center of the image mark the positions of the CMO mooring arrays. The wind velocity, measured at the central CMO mooring, at the collection time was about 5 m/s from 130˚ T. Internal waves can be seen throughout the scene with a strong packet near the lower left corner. Such internal-wave packets are generated on each diurnal tidal cycle by flow interactions with the continental-shelf break about 100 km or so to the south of the scene center [Gasparovic, et al., 1988]. (The streak just above the position of the left-most mooring is the signature of a ship wake. The bright point at the right end of the streak, displaced slightly below, is the microwave reflection from the ship.) The complicated structure of the internal-wave signatures in this image illustrates the difficulty of inferring properties of a two-dimensional internal wave field based on measurements from a single point sensor. The 2-d 'snapshot' provided by the SAR image simplifies significantly interpretation of time-series measurements from point sensors on the moorings. Further details of this topic may be found in Porter, *et al*., [2000] submitted for publication in the CMO special issue of *JGR-Oceans*.

We have recently shown how it may be possible to remotely estimate various properties of the water column on the continental shelf using SAR imagery in conjunction with knowledge of the local bathymetry, climatological density data, and simple models for internal-wave evolution [Porter and Thompson, 1999]. Theoretical studies of two-layer fluids indicate that dissipation of internal waves propagating into shoaling water occurs when the depth of the bottom layer, which is decreased by the shoaling, becomes equal to that of the upper layer. Using this idea, we have determined this critical depth for particular case studies selected from our CMO data base by noting the location in the SAR

Figure 1: SAR image of the CMO area collected on 31 May 1997 at 22:36 UT. The white squares mark the location of the four primary mooring arrays deployed for the CMO experiment.

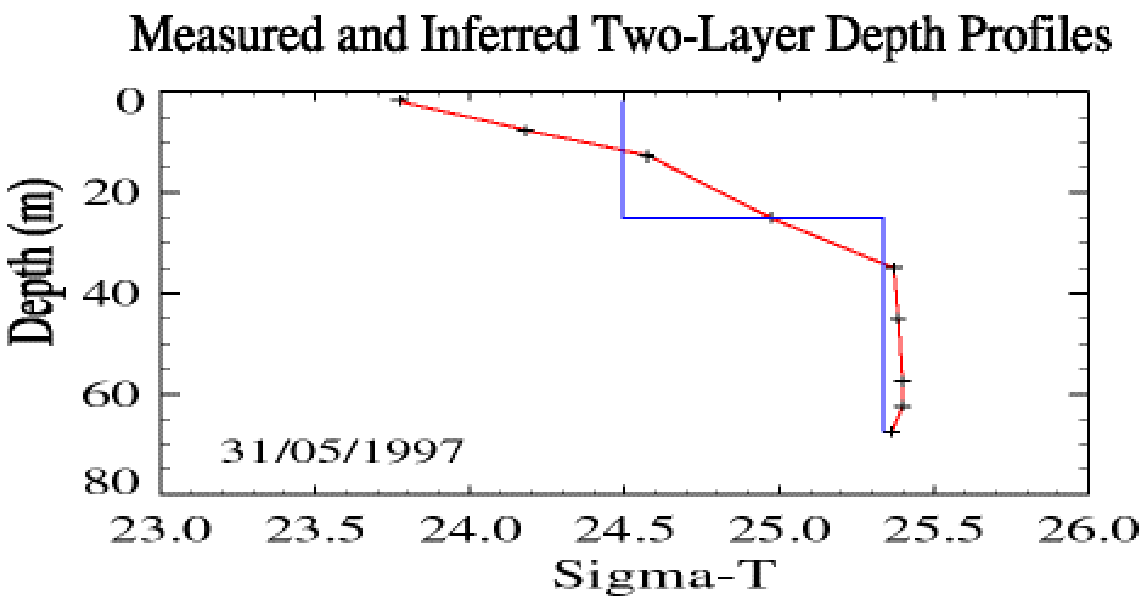

Figure 2: Plot of the density structure at the central CMO mooring on 31 May 1997 at 22:36 UT. The crosses are measured densities from the CMO mooring (connected by red line segments), and the blue curve shows the best-fit two-layer profile.

image where the internal-wave surface signatures disappear. The depth of each layer at this position is then half the total depth. By assuming that the internal waves are generated at the shelf break on each diurnal tidal cycle as discussed above, we can also estimate their phase speed by measuring the distance between successive packets in the image. With this information along with a 2-layer dispersion relation, we have been able to estimate the fractional density change between the two layers. An estimate of the absolute density of the surface layer is possible if the bottom-layer density is independently known; from climatological records for example.

We have compared the parameters extracted from the SAR imagery using the methods discussed above with *in situ* measurements collected concurrently at the CMO moorings. For example, the density profiles (provided by Steve Lentz of WHOI) measured at the central mooring on 31 May 1997 at the time of the image shown in Figure 1 are shown by the crosses in Figure 2. (The red curve in the figure connects these measurements.) From these data, we have computed a best-fit two-layer density profile that preserves the mass of the water column. Such a profile is shown by the blue curve in Figure 2. The parameters of this best-fit two-layer profile are then compared with those inferred from the SAR imagery using the procedures discussed in Porter and Thompson, [1999]. A summary of this comparison for the 31 May 1997 image discussed above as well as two additional cases from the CMO data base is shown in Table 1.

Table 1: Summary of continental shelf parameters inferred from SAR imagery.

	SAR-Inferred Parameters				**Mooring Observations**		
Date	h_1	h_2	C_p	ρ_1	ρ_1	ρ_2	h_1
1996 Sep 28	31.5 m	62.5 m	0.34 m/s	23.78	23.75	24.525	35 m
1996 Sep 28	32.5 m	67.5 m	0.34 m/s	23.80	23.75	24.525	35 m
1996 Sep 28	33.5 m	72.5 m	0.34 m/s	23.82	23.75	24.525	35 m
1997 May 31	21.5 m	51.5 m	0.50 m/s	23.36	24.49	25.387	25 m
1997 May 31	23.5 m	68.5 m	0.50 m/s	23.54	24.49	25.387	25 m
1997 May 31	25.5 m	85.5 m	0.50 m/s	23.65	24.49	25.387	25 m
1997 Jun 01	21.5 m	51.5 m	0.53 m/s	23.13	24.69	25.350	25 m
1997 Jun 01	24.5 m	68.5 m	0.53 m/s	23.37	24.69	25.350	25 m
1997 Jun 01	27.5 m	85.5 m	0.53 m/s	23.53	24.69	25.350	25 m

Three independent cases from three different days are presented in Table 1. For each case, we present three values for the relevant parameters corresponding to uncertainties in our estimates of the depth of the thermocline (h_1). Note that the SAR-inferred values for h_1, the bottom-layer depth (h_2), and the phase speed of the internal waves (C_p) are determined entirely from the SAR imagery, and are independent of the mooring observations [Porter and Thompson, 1999]. We then use the value of the bottom-layer density, ρ_2, as determined from the two-layer fit to the mooring data along with the other SAR-inferred parameters to solve the two-layer dispersion relation for the upper-layer density ρ_1. To assess the validity of our technique, we compare the values of h_1 and ρ_1 from the SAR-inferred and mooring-observation columns in Table 1. (Direct estimates of the internal-wave phase speed based on the mooring observations were not available at the time of this report.) For the 1996 Sep 28 case, we see that the estimated depth is 32.5 m and the observed depth is 35 m. This can be considered a very close comparison due to the fact that the sensors on the mooring array were separated by 5 m or more. The measured and inferred surface densities show nearly perfect agreement. For the 1997 May 31 case we see that the estimated depth is 23.5 m and the observed depth is 25 m. The inferred surface density however, is almost 1 sigma value smaller than the observed. A similar result is found on the next day as well. We believe this discrepancy could be due to advection effects (from tidal currents, for example) that were neglected in our estimates of the internal wave phase speed. A decrease in C_p by about 0.15 m/s on both of the latter two days brings the SAR-inferred value of ρ_1 into good agreement with the mooring observations. Thus we see from these examples that our technique for extracting water-column parameters from SAR does produce reasonable results, but refinements are clearly needed before it is ready for routine operational use. This is an area of ongoing research.

IMPACT/APPLICATIONS

The imagery collected in support of the CMO program is unique among remote-sensing data sets. It constitutes probably the most densely-sampled time series of satellite SAR imagery over a fixed oceanographic location yet to be acquired. Almost every image in this series is supported not only by nearly concurrent AVHRR imagery, but also by precisely the required *in situ* data necessary for validation and refinement of the models that govern the imaging physics. It has become apparent during the course of the CMO that the 2-dimensional view of the ocean surface provided by the imagery can greatly reduce the difficulty in the interpretation of *in situ* data from point sensors. Moreover, by utilizing the combined data set, we have begun to develop and validate techniques for extracting important oceanographic information from the imagery. Further refinement of such techniques could eventually lead to the routine use of remote-sensing methods as an operational tool for oceanographic research.

TRANSITIONS

All of the imagery analyzed as part of the CMO effort along with relevant ancillary data has been made available over the World Wide Web to other investigators who may need the data. Since our initial involvement in the CMO experiment three years ago, we have had many requests from investigators interested in SAR imagery to support their oceanographic experiments. This is apparently an indication that ocean remote-sensing data is no longer a novelty, but rather can now be considered as a useful tool for the general oceanographic community.

RELATED PROJECTS

The research described in this report has general relevance to various Navy programs concerned with the remote sensing of littoral processes. In a related project (in collaboration with Al Plueddemann at WHOI), we are comparing 2-D surface wave spectra, measured from a pitch-roll buoy deployed during CMO, with those derived from the SAR imagery. These comparisons are especially interesting during the passage of Hurricane *Edourad* near the CMO experimental site in early September 1996. This investigation is in turn directly relevant to our efforts for the wave-coherence working group of the ONR-sponsored Mobile Offshore Base (MOB) program. The internal-wave analysis component of our CMO research is also important for ongoing research to extract high-resolution wind fields from SAR. In this study, an important problem is the separation of signal variance in the imagery caused by oceanic signatures (such as those from internal waves) from variance induced directly by wind fluctuations. Both of these latter efforts are funded by ONR Remote Sensing and Space and are currently underway in our group at JHU/APL. Finally, we have a masters-degree student correlating the phase of tidal flow over Nantucket Shoals with the surface signatures of these features in our SAR-image time series.

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PUBLICATIONS

Porter, D. L. and Thompson, D. R., "Continental shelf parameters inferred from SAR internal wave observations", *J. Atmospheric and Oceanic Tech*., **16**, 475-487, 1999.

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